EXAMINATION OF THE SAFETY IMPACTS OF VARYING FOG DENSITIES:
A CASE STUDY OF I-77 IN VIRGINIA

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ABSTRACT

Fog can represent a significant safety hazard for motorists. While several studies have examined how fog crashes differ from crashes in clear conditions, they have treated fog as a homogeneous condition and not considered the safety impact of varying fog densities. I-77 in Fancy Gap, Virginia was used as a case study to better understand how safety changes as a function of available visibility. This study used crash, speed, visibility, and traffic data to characterize typical fog events, determine differences in crash characteristics by the severity of fog, and determine how speed profiles change with the density of fog. The analysis found that crashes in fog are more likely to be severe and involve more than two vehicles, supporting the findings of prior studies. While drivers reduce their speed in fog, the mean speeds exceeded safe speeds under all fog conditions. Examination of crashes and speed profiles by severity of visibility reduction showed that the level of available visibility impacts safety. The analysis showed that the presence of any fog has a negative effect on safety, with differential effects being observed depending on the severity of visibility reduction. Safety worsened when visibility drops below the stopping sight distance for the roadways, and then further degraded when visibility dropped below 360 feet. The results show that safety impacts of fog are not uniform across fog densities, and that mitigation efforts should be focused on areas experiencing recurring dense fog.
INTRODUCTION

Reduced visibility created by fog can create a significant safety hazard, particularly on high-speed roads. Past studies have shown that crashes in fog tend to involve multiple vehicles and have a higher percentage of fatalities and injuries than crashes in clear conditions (1). Fog is often unpredictable and fast setting, which can make it difficult for transportation agencies to address safety issues created by fog. Until recently, there have been relatively few engineering countermeasures that could address safety during foggy conditions.

Variable speed limit (VSL) systems are a type of intelligent transportation technology that dynamically set speed limits based on roadway conditions. Weather controlled VSL systems use atmospheric data to calculate a safe driving speed that is displayed on VSL signs. Typically, these systems are used to improve safety in winter weather or low visibility.

Past research has focused on how safety differs during foggy versus clear conditions using police crash reports. The definition of what constitutes “fog” is often not well-defined on these crash reports, however. As a result, crashes that happen during severe, dense fog are often combined with crashes that occurred during periods when fog was present but visibility distance exceeded required stopping sight distance (SSD). This aggregation of crash data across different visibility levels could mask changes in driver behavior and crash characteristics that could be important as fog becomes denser. These differences would need to be accounted for in any potential weather VSL system that is deployed. A greater understanding of driver speed behavior across the continuum of visibilities present during fog is needed.

LITERATURE REVIEW

Most prior safety studies of fog examine aggregate safety impacts without differentiating between fog densities. One recent study reviewed two decades of crashes during low-visibility conditions throughout the United States. The crash analysis examined fatal crashes from 1990 to 2012 collected from the Fatality Analysis Reporting System and all crash severities using data from the National Automotive Sampling System General Estimates Systems between 1990 and 2008 (1). The results from the crash analysis found that, in general, the raw number of fatal crashes in fog has decreased over the study period (1). Possible explanations for this trend include improvements in weather monitoring and driver alert systems, changes in crash coding, as well as overall improvements in vehicle safety. Since the study did not account for changes in exposure, it is also possible that there were fewer foggy days over time. The analysis supported the common belief that fog crashes are often likely to involve multiple vehicles. According to the report, 20 percent of fatal crashes involving 10 or more vehicles and 4.5 percent of crashes involving 6 to 9 vehicles occur in fog (1). The report concluded that while fog crashes are a small percentage of overall crashes, crashes are more likely to occur in low visibility conditions than in clear conditions and that these crashes are more likely to be serious and involve multiple vehicles (1). There are several limitations with this crash analysis, however. There was no attempt to correct for exposure in terms of vehicle-miles of travel (VMT) or days of exposure to different conditions. Furthermore, there was no analysis of the severity of the fog. Crash trends and characteristics may vary by the severity of the visibility reduction.
A study of crashes in Florida from 2003 to 2007 looked at various factors that might contribute to fog and smoke crashes such as lighting, posted speed, number of lanes, median type, and driver age (2). Odds ratios were calculated to examine crash type and severity for fog and smoke crashes compared to crashes in clear conditions (2). This analysis revealed that crashes in fog or smoke were more likely to have a fatality or severe injury and involve multiple vehicles than crashes in clear conditions (2). Head-on crashes were found to be the most likely crash type for fog or smoke crashes, however this dataset included undivided roadways as well as divided highways (2). This study also did not examine the severity of the visibility reduction.

Several other studies looked at raw numbers of crashes in fog compared to crashes in clear conditions; however no analysis was performed with regard to crash cause or characteristics (3, 4). One study of crashes in fog as well as other adverse weather conditions focused on economic impacts and mitigation techniques, but did not look at contributing factors (5).

Relatively limited research has been performed regarding the causes and characteristics of crashes during fog. Several studies examined raw numbers of crashes by type and severity, but there is a gap in research regarding changes in safety and driver behavior by visibility level. This is likely due to a general lack of visibility data over an extended period of time on a widespread basis.

OBJECTIVES AND SCOPE

This study sought to determine how safety at a site changes as a function of available visibility during fog. The study used crash, speed, visibility, and traffic data from an instrumented test corridor that was prone to fog events to achieve several objectives:

- Characterize the distribution of the severity of fog events
- Determine differences in crash characteristics by the severity of fog
- Determine how speed profiles and compliance changes with severity of fog

While the data analysis is limited to a single interstate corridor in Virginia, the analysis should show whether the treatment of fog as a homogeneous state, as done in earlier studies, is appropriate or if the severity of fog has differential impacts on safety.

METHODOLOGY

Site Description and Data Collection

I-77 in Fancy Gap, VA is a four-lane divided interstate with a posted speed limit of 65 mph and a 2014 Annual Average Daily Traffic (AADT) of approximately 18,000 vehicles per day in each direction. The site has road weather information system (RWIS) stations at twelve locations over approximately 16 miles which provide a dense network of visibility readings along the corridor. Speed data was available at a single location on the corridor. The site is rural, and the Virginia Department of Transportation (VDOT) indicated that this site had a relatively large proportion of through drivers unfamiliar with the corridor. Figure 1 shows the locations of the data collection sites. A VSL system that changes speeds as a function of visibility is currently
under construction in the corridor, but it was not active during the study period documented in this paper.

FIGURE 1: Site Location

Visibility Data

On I-77, Vaisala RWIS weather stations with visibility sensors were located at mile points (MP) 1.2, 1.8, 2.7, 3.0, 4.4, 5.3, 6.6, 7.3, 9.0, 9.6, 11.3, and 16.9. The visibility sensors used the forward scatter measurement principle to measure the meteorological optical range (6). Visibility data were collected every ten minutes, and sensors were located 20 feet above the surface of the road. The dense spacing on the corridor was due to recurring fog problems on the corridor, and several severe, multi-vehicle crashes have occurred at the site (7). This visibility data was used to construct a profile of the severity of fog events spatially across the corridor from 2010 to 2014.

Crash Data

All police crash reports from 2010 to 2014 were compiled from VDOT’s Road Network System (RNS). The weather conditions field on the police report was used to identify crashes that occurred in fog. The crash data were used to examine whether characteristics of crashes along the corridor varied by visibility condition.

Traffic Data

Available traffic count data for the study period were also collected from RNS so that a measure of exposure could be determined. Since there were no continuous count stations active in the corridor for the entire study, available short-term counts were used with expansion factors. The methodology used to develop vehicle miles of travel (VMT) estimates is discussed later in the paper.
**Speed Data**

Although visibility data was available since 2010, speed sensors were only installed in September 2014. A single Wavetronix speed sensor was installed in the southbound direction on a sustained downgrade of approximately -4% at MP 6.6. The southbound direction was selected for study since it represented a worst case scenario for speed during fog conditions. Traffic data were recorded in five minute bins for vehicles traveling in the southbound lanes of I-77. The data collected included volume by vehicle class, mean speed, and 85th percentile speed. Vehicle speeds were tabulated in five minutes bins used to calculate standard deviation of speed.

Speed and weather data were matched by timestamps. Because the weather data were reported every ten minutes and speed data were reported every five minutes, visibility was linearly interpolated between ten minutes readings to get estimated visibility data in five minutes intervals. Speed and visibility data were both available for eight low visibility events between September 2014 and March 2015, representing approximately 180 hours of data.

**Analysis**

For this analysis, any visibility measurement below 645 feet was considered “low visibility”. This threshold corresponds with a safe speed of 65 mph based on the safe stopping sight distance equation (Equation 1), assuming a flat grade and a 2.5 second perception-reaction time. Since the corridor contains both uphill and downhill sections, a flat grade was assumed in order to have a consistent basis for summarization. Since I-77 has a 65 mph posted speed limit, there should theoretically be no need to reduce speed when visibilities exceed 645 feet.

\[
SSD = 1.47 \times V \times 2.5 + \frac{1.075 \times V^2}{11.2 \text{ ft/s}^2}
\]

(Eq. 1)

Where

- \(SSD\) = Stopping sight distance (feet)
- \(V\) = Speed (mph)

Observation of the speed data suggests driver speeds do not vary with visibility above this 645 feet threshold. The visibility was further divided into bins according to the safe stopping sight distance speed:

- >645 feet – 65 mph
- 495 to 645 feet – 55 mph
- 360 to 495 feet – 45 mph
- 250 to 360 feet – 35 mph
- 155 to 250 feet – 25 mph
- <155 feet – <25 mph

These bins were used to characterize crashes, speed, and standard deviation of speed by visibility condition.
Visibility Profile

Visibility data was compiled for 2010 to 2014 for the twelve RWIS stations in order to determine the frequency and magnitude of fog events. Visibility was assigned into the safe stopping sight distance analysis bins based on available visibility, and the hours of low visibility each year was calculated for each RWIS station.

Crash Analysis

Crashes were matched with visibility data so that crashes in varying degrees of low visibility could be compared to crashes in clear conditions. Crash severity, collision type, and number of vehicles involved in the crash were all tabulated for easy comparison of the proportions of crashes in each visibility bin.

Crash rates were also calculated on the corridor using visibility and crash data from 2010 to 2014. Since real-time volume data were not available throughout the corridor, hourly volume profiles were determined using available short-term counts which were assumed to represent the temporal distribution of travel on I-77 for all days. The yearly AADT was multiplied by this hourly distribution to get an estimated hourly AADT for a given day in each analysis year.

Visibility data was used to calculate the hourly breakdown of visibility in each of the visibility bins. The vehicles miles traveled (VMT) was then calculated by multiplying hourly AADT by the hours of visibility throughout the year recorded in that bin in that hour of the day. Finally, each of the 24 hourly VMTs were summed to get the VMT for each of the analysis years. The crashes were each assigned a visibility and placed in the appropriate bin. Since this site is in a rural area and does not experience significant variability in traffic, this approach is expected to provide a reasonable estimate of VMT.

Speed Analysis

Crashes are an obvious indicator of safety, but because they are random events it may be difficult to get a large enough sample to draw meaningful conclusions. Alternatively, speed and standard deviation can be used as a surrogate indicator to evaluate safety. Mean speeds, standard deviation of speed, and coefficient of variation are calculated for each visibility bin so that behavior in low visibility can be compared to behavior in clear conditions. For each five minute observation, the number of vehicles exceeding the safe speed based on stopping sight distance was determined to measure compliance with safe speed by visibility condition. The pace speed and the percentage of vehicles traveling in the pace were also examined to assess the amount of consistency in travel speeds.

RESULTS AND DISCUSSION

Visibility

Figure 2 shows the visibility profile for the study section using all data from 2010 to 2014. The purple line shows the percentage of time that the RWIS sensor was reporting reduced visibility, once invalid readings were removed from the analysis. Figure 2 shows that the distribution of
fog varied spatially along the corridor. The worst visibility occurs between mile post 4.4 and 7.3, with MP 6.6 observing reduced visibility for more than 5% of the year on average. The proportion of very severe fog events was also higher at MP 5.3 and 6.6 versus other sites. Thus, even within this relatively short corridor, the characteristics of fog varied substantially. This may indicate that treating fog as a homogeneous condition may not be appropriate.

![FIGURE 2: Average Distribution of Low Visibility Events on I-77 in Fancy Gap, Virginia, 2010-2014](image)

**Crash Frequency**

Police crash reports were used to analyze crashes from 2010 to 2014 on I-77 between MP 0 and mile point 15. The four year crash history revealed 524 total crashes with 77 “fog” crashes coded on the police crash report. Each crash was assigned a visibility reading by matching data from the RWIS stations using the timestamp and mile point listed on the crash report. Linear interpolation between stations and 10 minute readings was used to estimate the visibility associated with each crash.

After performing the matching, 58 crashes could be associated with visibility measurements less than 645 feet, representing 11% of the total crashes during this time period. This indicates that crash likelihood is higher than would be expected based purely on the amount of time when fog was present in the corridor, as shown in Figure 2. It also means that 19 of the 77 crashes where police recorded fog on the crash report actually occurred during periods when there was no visibility reduction that should have significantly adversely impacted safety. This shows that the definition of fog is inconsistent with a SSD based definition, and perhaps shows inconsistent definition and interpretation of fog by reporting officers. The 58 crashes occurred on 10 different days all between September and May. Of these crashes, 49 occurred in the southbound
direction and 9 occurred northbound. Rear end collisions were the most common crash type, consisting of 37 crashes (63.8%). There were five fatal crashes and 23 injury crashes.

Table 1 shows the breakdown by crash severity for crashes during clear conditions and fog crashes. The table shows that fatal and injury crashes make up a greater proportion of crashes during fog versus clear conditions, which is supported on a larger scale in the AAA Foundation report (1). During reduced visibility, fatal and injury crashes are almost twice as common as they are during clear conditions (48% vs. 25%). The proportion of injury and fatal crashes shows no clear trend across the visibility categories, so there is no indication of increasing likelihood of fatal or injury crashes as fog gets more severe.
<table>
<thead>
<tr>
<th>Visibility Bin</th>
<th>Fatal</th>
<th>Injuy</th>
<th>Fatal + Injury</th>
<th>Property Damage Only</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;645 ft, 65 mph</td>
<td>9</td>
<td>105</td>
<td>114</td>
<td>348</td>
<td>462</td>
</tr>
<tr>
<td>All Low Visibility</td>
<td>5</td>
<td>23</td>
<td>28</td>
<td>30</td>
<td>58</td>
</tr>
<tr>
<td>495-645 ft, 55 mph</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>360-495 ft, 45 mph</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>250-360 ft, 35 mph</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>155-250, 25 mph</td>
<td>2</td>
<td>15</td>
<td>17</td>
<td>20</td>
<td>37</td>
</tr>
<tr>
<td>&lt;155 ft, &lt;25 mph</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Error, no visibility information</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>All Conditions</td>
<td>14</td>
<td>130</td>
<td>144</td>
<td>380</td>
<td>524</td>
</tr>
</tbody>
</table>
The AAA Foundation report also found that a high proportion of fatal crashes in fog involved multiple vehicles (1). The data from I-77 suggests a similar trend. Table 2 shows the proportions of crashes that had a given number of vehicles involved in the crash. Table 2 indicates that in clear conditions, only 47% of crashes on the corridor involved multiple vehicles. During fog, this number increases to an average of 91%. The percentage of crashes involving 3 or more vehicles was more than 4 times greater during foggy versus clear conditions (45% vs. 10%). The proportion of multiple vehicle crashes appeared to increase as visibility degraded. Between 360 and 645 feet of visibility, approximately 80 percent of crashes involved more than 1 vehicle. This increased to 97 percent when visibility was between 155 and 360 feet. Only one crash was observed in visibility lower than 155 feet and it involved only 1 vehicle.

Table 2: Number of Vehicles Involved in Crashes by Visibility Bin, 2010-2014

<table>
<thead>
<tr>
<th>Visibility Bin</th>
<th>Number of Vehicles Involved in Crash</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>&gt;645 ft, 65 mph</td>
<td>246</td>
<td>172</td>
</tr>
<tr>
<td>All Low Visibility</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>495-645 ft, 55 mph</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>360-495 ft, 45 mph</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>250-360 ft, 35 mph</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>155-250 25 mph</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>&lt;155 ft, &lt;25 mph</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Error, no visibility information</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>All Conditions</td>
<td>253</td>
<td>201</td>
</tr>
</tbody>
</table>

Table 3 shows the breakdown by crash type for fog crashes and crashes during clear conditions. Rear-end crashes represent 64% of fog crashes compared to 25% of crashes during clear conditions. This trend coincides with the finding of increased multiple vehicle crashes shown in Table 2. Not surprisingly, the proportion of rear end crashes appears to be greater as the visibility conditions decline. While the likelihood of rear end crashes is higher overall during fog, it appears that the risk of rear end crashes is particularly high as the safe speed drops below 45 mph. This suggests that drivers are more prone to traveling too fast for conditions as visibilities are significantly reduced.
<table>
<thead>
<tr>
<th>Visibility Bin</th>
<th>Rear End</th>
<th>Fixed Object – Off Road</th>
<th>Angle</th>
<th>Sideswipe – Same Direction</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;645 ft, 65 mph</td>
<td>116</td>
<td>178</td>
<td>3</td>
<td>45</td>
<td>100</td>
<td>462</td>
</tr>
<tr>
<td>All Low Visibility</td>
<td>37</td>
<td>3</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>495-645 ft, 55 mph</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>360-495 ft, 45 mph</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>250-360 ft, 35 mph</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>155-250 25 mph</td>
<td>26</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>&lt;155 ft, &lt;25 mph</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Error, no visibility information</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>All Conditions</td>
<td>154</td>
<td>184</td>
<td>33</td>
<td>51</td>
<td>102</td>
<td>524</td>
</tr>
</tbody>
</table>
Crash Rate

While the crash frequency analysis provides some insight into crashes in fog, it does not control for exposure in any way. Some fog events occurred during low volume, overnight hours while others occurred during the day. In order to address this, crash rates were calculated per 100 million vehicle miles traveled and are shown in Table 4. This analysis shows that in worsening visibility conditions, the crash rates increase. Crash rates when safe speeds are less than 65 mph are more than double the crash rates experienced during clear conditions. The crash rates are greater in the southbound direction than the northbound direction, which was expected given the downhill grades in the southbound direction at the location with the worst visibility. While the general trend towards greater crash rates in low visibility compared to clear conditions is likely reliable, the magnitude of some of the calculated rates is driven by the relatively small sample size of crashes. In particular, the crash rates in the 25 mph safe speed bin were a function of a large number of crashes occurring during a few, very severe fog events.

While this analysis does show that fog is correlated with higher crash rates, the analysis has several limitations. Crash times and locations are taken from the police reports that are recorded at the scene following a crash. The accuracy of the time and location has a large effect on the visibility value assigned to the crash and subsequently which visibility bin it is placed in for the crash rate calculation. This analysis makes the assumption that there is a linear relationship in visibility between weather sensors and between ten minute sensor readings.

Another limitation is that real-time volumes are not available continuously throughout the corridor. Average hourly volume profiles were used to create estimates of AADT by hour, which may deviate from what was experienced at the site. This was expected to be a minor concern, however, since fog events would be expected to reduce volume, if anything. If volumes dropped during fog, then the crash rates would be even higher than what is shown in Table 4.

<table>
<thead>
<tr>
<th>Visibility Bin</th>
<th>Number of Crashes</th>
<th>Crash Rates (Crashes per 100 Million VMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North</td>
<td>South</td>
</tr>
<tr>
<td>&gt;645 ft, 65 mph</td>
<td>231</td>
<td>231</td>
</tr>
<tr>
<td>495-645 ft, 55 mph</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>360-495 ft, 45 mph</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>250-360 ft, 35 mph</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>155-250 ft, 25 mph</td>
<td>6</td>
<td>31</td>
</tr>
<tr>
<td>&lt;155 ft, &lt;25 mph</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Error, no visibility information</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>All Conditions</td>
<td>242</td>
<td>282</td>
</tr>
</tbody>
</table>

Speed Analysis

Given that the crash data shows changes in crash characteristics as visibility declines, driver speeds were examined further to determine whether they were appropriate for conditions. Results from the speed analysis of I-77 at MP 6.6 are shown in Table 5. The N column...
represents the number of 5-minute periods in each visibility bin. Table 5 shows an overall trend that speeds decrease as visibility decreases. However, speeds are often far greater than the SSD based safe speed, particularly in the lowest visibility bins.

Standard deviation of speed is sometimes used as a surrogate measure of safety since it represents the variability of speeds on a road. It appears that standard deviation remains relatively consistent with visibility condition. At approximately 9 mph, the standard deviation is higher than expected for an interstate highway but may be a result of the steep grade and heavy truck traffic.

Since mean speeds are declining as visibility drops, the coefficient of variation may be a better measure of the dispersion of speed data since it accounts for the amount of variation relative to the mean speed. The coefficient of variation appears constant in visibility 250 feet to 645 feet, and then continues to increases in the visibility greater than 250 feet. This potentially indicates a higher likelihood of severe interactions between vehicles at these severely reduced visibilities.

Compliance with the SSD may also provide an indicator of safety across visibility levels. In all reduced visibility bins, at least 74% of drivers are exceeding the stopping sight distance safe speed. In the lowest visibility bin nearly every vehicle is exceeding the stopping sight distance safe speed. The same trend is apparent with the percent of vehicles driving within 10 mph of the stopping sight distance safe speed. In fact, for safe speeds of 45 mph or less, over 90% of vehicles are exceeding the SSD and over 71% are traveling more than 10 mph above the SSD.
<table>
<thead>
<tr>
<th>Visibility Bin</th>
<th>SSD (feet)</th>
<th>n</th>
<th>Mean Speed (mph)</th>
<th>Standard Deviation (mph)</th>
<th>Coefficient of Variation</th>
<th>Pace Speed</th>
<th>% of Vehicles Traveling in Pace</th>
<th>Percent Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;645 feet</td>
<td>&gt;645</td>
<td>973</td>
<td>66.9</td>
<td>8.69</td>
<td>0.13</td>
<td>65-75 mph</td>
<td>49%</td>
<td>n/a</td>
</tr>
<tr>
<td>495-645 feet</td>
<td>495-645</td>
<td>250</td>
<td>61.7</td>
<td>9.37</td>
<td>0.16</td>
<td>60-70 mph</td>
<td>44%</td>
<td>74%</td>
</tr>
<tr>
<td>360-495 feet</td>
<td>360-495</td>
<td>404</td>
<td>60.7</td>
<td>9.11</td>
<td>0.15</td>
<td>60-70 mph</td>
<td>43%</td>
<td>92%</td>
</tr>
<tr>
<td>250-360 feet</td>
<td>250-360</td>
<td>683</td>
<td>57.5</td>
<td>8.99</td>
<td>0.16</td>
<td>55-65 mph</td>
<td>44%</td>
<td>98%</td>
</tr>
<tr>
<td>155-250 feet</td>
<td>155-250</td>
<td>737</td>
<td>51.2</td>
<td>9.09</td>
<td>0.18</td>
<td>50-60 mph</td>
<td>38%</td>
<td>98%</td>
</tr>
<tr>
<td>&lt;155 feet</td>
<td>&lt;155</td>
<td>9</td>
<td>44.3</td>
<td>9.39</td>
<td>0.22</td>
<td>45-55 mph</td>
<td>38%</td>
<td>99%</td>
</tr>
</tbody>
</table>
Figure 3 shows the aggregate distribution of vehicle speeds for each visibility category using data from all fog events since September 2014 at MP 6.6. The distribution appears relatively consistent for visibilities between 360 and 645 feet. For visibilities less than 360 feet, the profile for each subsequent lower visibility bin shifts to the left. For each of these bins, the peak also appears increasingly spread out. This is reflected by the percentage of vehicles traveling the pace speed as shown in Table 5. During clear conditions, nearly 50 percent of vehicles are traveling in the 10 mph pace. Under the worst visibility category, about 38 percent of vehicles are traveling in the 10 mph pace. This spreading of the peak will likely increase interactions between vehicles traveling at different speeds, which could create negative safety effects.

![FIGURE 3: Speed Profiles by Visibility Bin](image)

The speed analysis findings reinforce the crash analysis findings presented earlier. As fog becomes more severe, the deviations between the safe speed and the observed travel speeds increase. Since drivers are over-driving the available visibility, this will lead to increased conflicts between vehicles and more rear end and multi-vehicle crashes. The speed data also supports the findings that safety concerns become increasingly severe when visibility drops below a 35 to 45 mph safe speed. Additional attention to driver performance and behavior in those very severe conditions appears to be warranted.

CONCLUSIONS

This is the first study to look at both crashes and speed as a function of the severity of the fog event. Prior research has treated fog as a homogeneous weather condition, but this study
indicates that crash characteristics and risk change as fog density increases. The analysis showed that crashes in fog are more likely to be severe and involve two or more vehicles, corroborating prior studies. Drivers reduce their speed in low visibilities, but mean speeds exceeded safe speeds in all low visibility bins. Nearly all vehicles are exceeding the safe speed in the lowest visibility bins. This poor compliance with safe speed in low visibility helps explain the high crash rates during fog.

This research was able to look at how safety changes in the corridor as fog becomes denser. By looking at crashes and speed profiles by visibility bin, it is apparent that the level of visibility impacts safety. This analysis shows that the presence of any fog that restricts visibility below SSD has an effect on safety, as there is a change in crash and speed characteristics between clear conditions and the highest visibility bins. It then appears that speeds and crash characteristics change further when visibility dropped below 360 feet. The proportion of rear-end crashes and crashes involving multiple vehicles both increases, and crash rates were also extremely high in the 155 to 250 feet visibility range. While the speed profiles when visibility exceeds 360 feet are very similar, the profiles for the lower bins shows a shift to the left and a wider range of speeds at the peak. This increased speed dispersion at lower visibilities is likely the cause of the decreased safety in these visibility categories.

Although this research is based on only a single site, it provides a strong indication that areas that experience recurring fog events should consider the density of the fog when developing countermeasures, such as VSL systems. Freeways where fog events routinely restrict visibility below 360 feet may require significant investment in countermeasures, or DOTs may even want to consider policies where roadways would be closed due to increased fog risk.

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